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Simulation of operation of an open geothermal system with seasonal variations

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Abstract. A mathematical model for the operation of an open geothermal cyclic system for two wells is presented. The production well is supposed to pump hot water from an underground geothermal reservoir. After the use for heating purposes the cooled water is pumped back into the aquifer through the injection well. Various options related to the seasonal needs for hot water are investigated for operating such a system. During the summer months hot water is required in less quantities. The results of numerical calculations show that it is possible to choose such modes for greater efficiency and increase the time of operation of such a system.

1. Introduction

Geothermal energy is the heat of the deep layers of the earth, which are characterized by much higher temperature than the air temperature at the surface. The sources of such energy are geothermal reservoirs containing hot water or steam-water mixture. Unlike solar or wind energies, which are not available during calm weather or at night, the heat of Earth can be used continuously. The geothermal energy is unevenly distributed and not all the countries of the world have significant sources of this energy for the effective using. For example, countries that are located in volcanic regions of the planet do have this opportunity. Iceland managed to achieve high rates of life due to geothermal resources. More than 90% of the heat supply here is based on geothermal heat.

The areas of geothermal heat are widespread, but only the easy to use reservoirs are of practical importance. In this case, geothermal deposits with water temperature from 40°C to 100°C or 150°C are used for heat supply, and geothermal reservoirs having the temperature from 150°C to 300°C can be also used to generate electricity. Geothermal energy is one of perspective types of renewable energy. Even if using only the part of the earth's heat, which is located at a depth of 10 kilometers, the energy obtained will be several hundred times higher than that collected in all the world's oil and gas fields. In Russia, geothermal energy resources are comparable in volume with the hydrocarbon reserves. In southern Russia, geothermal waters generally have a temperature between 70°C and 130°C, which makes them usable for heat supply, while in Kamchatka geothermal resources allow to produce electricity.

However, the use of geothermal resources is associated with certain environmental risks, since emissions of waste cold water may contain highly mineralized or toxic impurity. Therefore, in geothermal stations, binary cycle technology is often used. In such systems, the geothermal fluid after use is immediately returned to the re-injection system, thereby completely replenishing the natural



geothermal reservoir and maintaining the necessary pressure in it. Such a hot water production system is called a geothermal cyclic system (GCS).

For mathematical modeling of GCS, the equations of underground hydrodynamics are used [1] to describe the flow in porous soil, taking into account the given soil lithology [2]. GCS may consist of two wells [3], [4], and of a number of wells [5]-[7]. One of the main problems of GCS mathematical modeling is to increase the time of operation of such a system due to the optimal choice of available parameters, in particular, the pressure created by the pumps of the production and injection wells, and the distance between these wells.

The presented work takes into account the thermophysical characteristics of the geothermal reservoir, the most significant technical parameters of wells, as well as possible seasonal variants of exploitation of such system, when in winter there is an increased use of hot water, and in summer this consumption may be significantly reduced.

For computational implementation of the described model two wells are considered: the producing well with hot water and the injection well with cold waste water. A numerical method is developed based on the ideas used in [2]-[4] and focusing on high-performance computer technologies.

2. Mathematical model and numerical algorithm

The heat transfer in the geothermal aquifer is carried out in two ways: convective and diffusion.

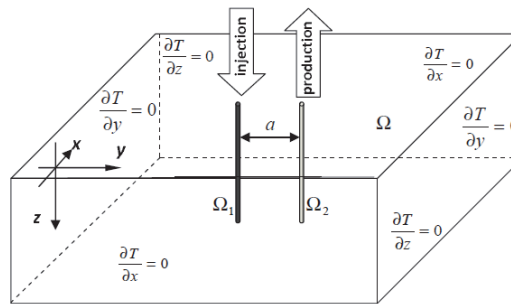


Figure 1. A geothermal open loop system with two wells.

Figure 1 presents a sketch of the operation of the GCS open loop system consisting of two wells. The injection well Ω_1 with the water temperature $T_1(t)$, and the production well Ω_2 , with the water temperature $T_2(t)$ are considered. It is supposed that $T_1(t) < T_2(0)$. To describe the processes of heat transfer and water filtration in a thermal reservoir the Darcy law and the law of conservation of mass (continuity equation) are taken into account. In general a system of equations for finding the pressure distribution and the velocity field of water filtration in the soil is formed. The equation for the pressure $p=p(t,x,y,z)$ is a piezoconductivity equation. As a result, the process of heat propagation $T=T(t,x,y,z)$ in the aquifer (in the computational region Ω) is described by the following equation [4]:

$$\frac{\partial T}{\partial t} + b \left(\frac{\partial T}{\partial x} u + \frac{\partial T}{\partial y} v + \frac{\partial T}{\partial z} w \right) = \lambda_0 \Delta T, \quad (1)$$

which is considered together with the equations for the components of the fluid filtration rate $\mathbf{V}=(u,v,w)$

$$\begin{cases} \frac{\partial u}{\partial t} = -\frac{1}{\rho} \frac{\partial p}{\partial x} - \frac{g\sigma u}{k} \\ \frac{\partial v}{\partial t} = -\frac{1}{\rho} \frac{\partial p}{\partial y} - \frac{g\sigma v}{k} \\ \frac{\partial w}{\partial t} = -\frac{1}{\rho} \frac{\partial p}{\partial z} - \frac{g\sigma w}{k} - g, \end{cases} \quad (2)$$

taking into account the continuity equation

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0, \quad (3)$$

$$\lambda_0 = \frac{\kappa_0}{\rho_0 c_0 (1 - \sigma) + \rho c_f \sigma}, \quad b = \frac{\sigma \rho c_f}{\rho_0 c_0 (1 - \sigma) + \rho c_f \sigma},$$

where ρ_0 and ρ are the soil and the water density in the aquifer, c_0 and c_f - are the specific heat of the soil and the water, and σ and κ_0 are porosity and heat conductivity of the soil, respectively. We assume that at the initial time moment the fluid in the productive layer is at rest, i.e. $u(0, x, y, z) = v(0, x, y, z) = w(0, x, y, z) = 0$. The piezoconductivity equation for the pressure in Ω has the form [8]

$$\frac{\partial p}{\partial t} = \omega \Delta p, \quad (4)$$

where ω is the piezoconductivity coefficient. The equations (1)-(4) for temperature and pressure in aquifer are solved using a finite difference method based on an approach of works [9]-[11]. Note that the computational area Ω with the aquifer have to be large enough to avoid artificial affecting the boundary conditions at the lateral boundaries.

3. Numerical results

The considered in [2]-[7] GCS was simulated without taking into account seasonal variations of exploitation, i.e. less hot water is needed to heat the buildings in summer and less cold water is

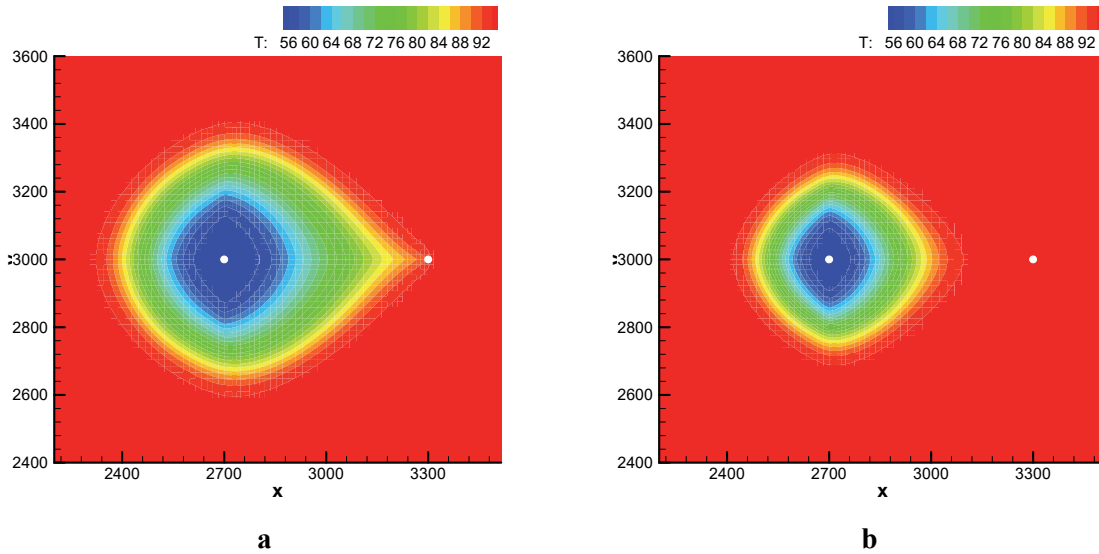


Figure 2. Temperature field in the 15th year of exploitation (**a** and **b**) in horizontal slice of the aquifer with the system of two wells: **a** and **b** correspond to the 100% and 50% of power during all the time of operation, respectively.

returned into the geothermal reservoir. This allows assuming that due to seasonal variations of the need for geothermal resources, it is possible to increase the life time τ of GCS. The life time τ is determined as follows: GCS exploitation is assumed to be over after the time τ , if the temperature of the injected water is closer to the extracted water or differs by the profitability of GCS.

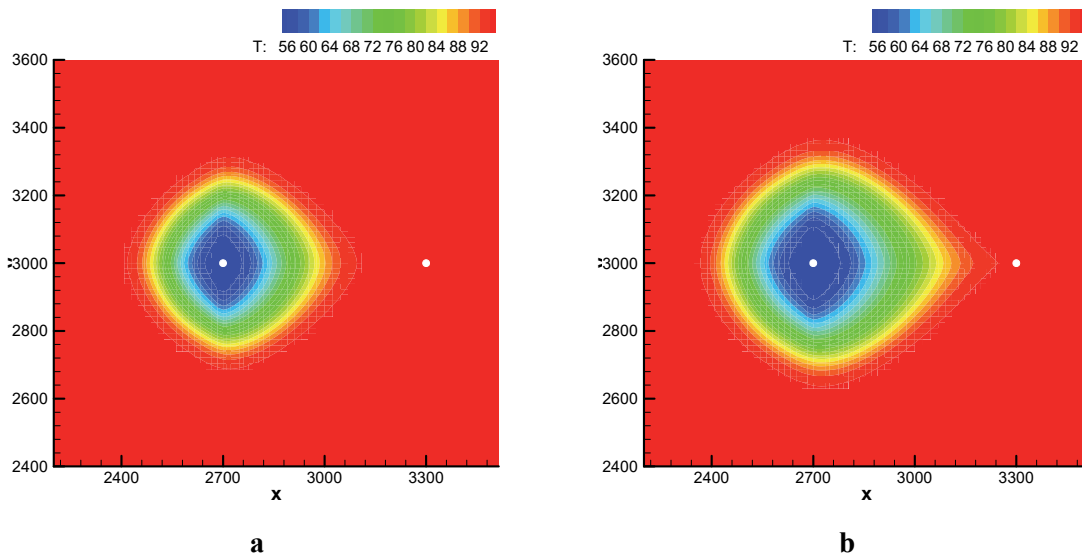


Figure 3. Temperature field in the 15th year of exploitation (**a** and **b**) in horizontal slice of the aquifer with the system of two wells: **a** and **b** correspond to 0.01% of the “summer” power during 6 months and 3 months of the annual operation, respectively.

Let the initial temperature of the considered aquifer be 95°C, and the released cold water temperature be 55°C. The basic thermal parameters of the aquifer are as follows: soil thermal conductivity is 2.00 [W/(m K)], soil volumetric heat is 2150 [kJ/(m³ K)], porosity is 0.241, and

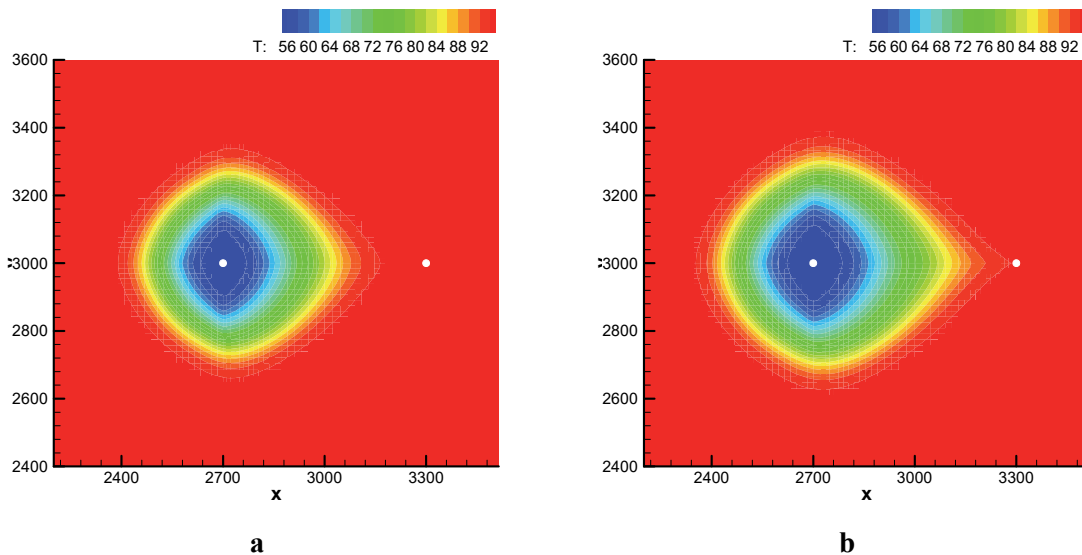


Figure 4. Temperature field in the 15th year of exploitation (**a** and **b**) in horizontal slice of the aquifer with the system of two wells: **a** and **b** correspond to 25% of the “summer” power during 6 months and 3 months annual operation, respectively.

velocity of filtration is $1.7 \cdot 10^{-5}$ m/s. The method of computation is an implicit finite difference method used with splitting by the spatial variables in three-dimensional domain to solve the problem [9]-[11]. Sizes of the area are 6000 m×6000 m×50 m. The GCS is in the center of the area. The computational time step is 1 day (86400 s) and the simulated period is 20 years.

The following figures illustrate the cold water movement from injection to producing wells after 5 years of GCS exploitation.

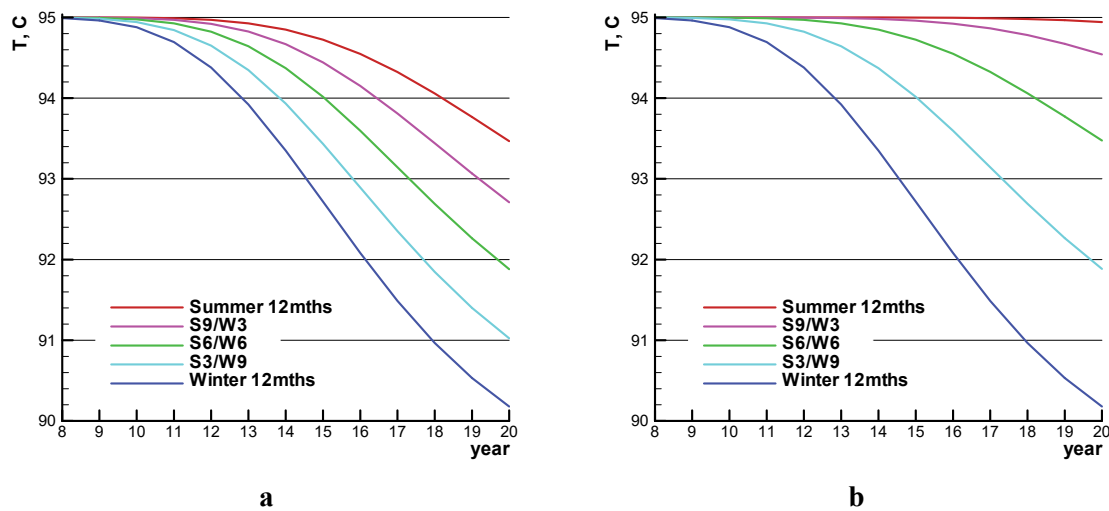


Figure 5. Production well temperatures for different relations of summer (S) and winter (W): **a** and **b** correspond to 75% and 50% of power during the summer, respectively.

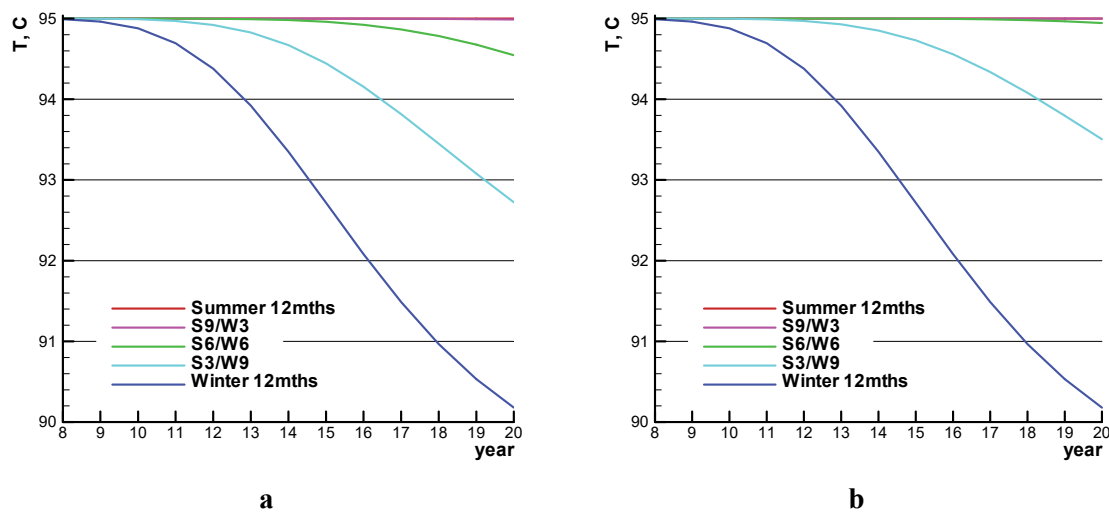


Figure 6. Production well temperatures for different relations of summer (S) and winter (W): **a** and **b** correspond to 25% and 0.01% of power during the summer, respectively.

In Figure 2a the distribution of cold water is shown (the temperature field in a horizontal plane) from the injected well with the fixed debit during all the year. The power is assumed to be 100% in winter. The temperature distribution is presented in Figure 2b for the case if the flow rate is reduced 2 times and the power is 50%.

In Figures 3a, 3b and Figures 4a, 4b the thermal fields in the aquifer are presented in a horizontal plane for the 15th year of exploitation of GCS with taking into account the summer decrease in the hot water needs. In the figures the percentage of pumps power decrease is shown.

Figure 3a presents thermal fields for the 6 months summer period when GCS is practically not used (0.01% of the maximum power). In Figure 3b thermal fields are presented for the case when the summer period is 3 months.

In Figures 5a, 5b and Figures 6a, 6b the temperature change in the production well is shown for various GCS operation options depending on the power and on the summer time period. In Figures 5, the following notations are used: SI/WJ, where I and J are the summer and winter months in the year, respectively. It is supposed that the power of GCS decreases by the given percent from the maximum power of GCS in the winter months.

Conclusion

The proposed model and the developed numerical algorithm allow carrying out simulations of temperature fields in an aquifer for various variants of operation of a GCS, consisting of two wells. It is shown that taking into account the seasonal decreasing of hot water production during the summer period helps to elongate the life time of the GCS and can have a significant impact on the dynamics of changes in water temperature in the production well. Therefore, when designing GCS, it is necessary to take into account not only the technical characteristics of the wells and the geothermal reservoir, but also the possibility of using different modes of hot water using, including, perhaps, not only winter and summer periods, but also other time intervals in which the GCS power is less than the maximum power.

Acknowledgments

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